

PSR J1753–2240: A mildly recycled pulsar in an eccentric binary system

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ABSTRACT

We report the discovery of PSR J1753–2240 in the Parkes Multibeam Pulsar Survey database. This 95-ms pulsar is in an eccentric binary system with a 13.6-day orbital period. Period derivative measurements imply a characteristic age in excess of 1 Gyr, suggesting that the pulsar has undergone an episode of accretion-induced spin-up. The eccentricity and spin period are indicative of the companion being a second neutron star, so that the system is similar to that of PSR J1811–1736, although other companion types cannot be ruled out at this time. The companion mass is constrained by geometry to lie above 0.48 solar masses, although long-term timing observations will give additional constraints. If the companion is a white dwarf or main sequence star, optical observations may yield a direct detection of the companion. If the system is indeed one of the few known double neutron star systems, it would lie significantly far from the recently proposed spin-period/eccentricity relationship.

Key words: pulsars: general — pulsars: individual: J1753–2240 — stars: neutron

1 INTRODUCTION

Several types of binary pulsar companion are known: main sequence stars, neutron stars, white dwarfs and even planetary-mass bodies (Lyne & Smith 2005). Pulsars in binary systems, especially those with neutron star companions, are valuable tools for studies of a variety of physics and astrophysics. However, white dwarfs are the most common type of companion, representing $\sim 90\%$ of all pulsar companions. White dwarf and neutron star companions are usually part of a binary pulsar system in which the pulsar has undergone a “recycling” process (e.g. Alpar et al. 1982). In this process, the pulsar forms first, spins down and ceases its normal radio emission phase before the companion evolves into a giant star, when it is likely to start overflowing its Roche lobe. Matter and angular momentum are transferred to the pulsar in an accretion process during which the system may be observable as an X-ray binary system (Bhattacharya & van den Heuvel 1991). In simple terms, the duration of the accretion process depends to a large extent on the mass of the companion star. A low-mass

companion will provide a long-lived accretion flow, allowing the pulsar to spin up to a period of a few milliseconds and to reappear as a radio source. In cases of more massive companions, a high-mass X-ray binary is formed in this “standard scenario”. Alternative models involving a “double core scenario” have been proposed (Brown 1995; Dewi et al. 2006). Common to both models is the occurrence of an evolutionary stage before the second supernova explosion (SN) which involves a helium star and the neutron star in a tight circular orbit (van den Heuvel & Taam 1984; Dewi & Pols 2003). Depending on the orbital period and the mass of the helium star, matter may be transferred from the helium star to the neutron star (e.g. Dewi & van den Heuvel 2004), for a period of time which determines the final spin period of the pulsar. The result is a mildly recycled pulsar with a period of tens of milliseconds, being significantly greater than the few milliseconds of a fully recycled pulsar.

Significant eccentricity is only expected if a binary system experiences a second supernova explosion, which may be the case in a high mass system. If the system survives this further SN, a double neutron star system (DNS) will be formed. Such DNSs are rare, only eight being known in the Galactic disk. The most exciting DNSs are compact,

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relativistic binaries in which a number of relativistic effects can be observed, so that they can be used for tests of theories of gravity. The best examples for this type are the Hulse-Taylor pulsar, PSR B1913+16 (Hulse & Taylor 1975) and the Double Pulsar, PSR J0737–3039A/B (Burgay et al. 2003; Lyne et al. 2004). While in the Double Pulsar both neutron stars are active and detectable radio pulsars, usually only the old, recycled pulsar is observed. An exception is the case of PSR J1906+0746, where we seem to observe the second-born, young pulsar (Lorimer et al. 2006; Kasian 2008). Other, less compact types of DNS with orbital periods of many days rather than hours exist, and it is likely that some of them have been formed via a wind-accretion phase rather than an accretion disk process as in the standard scenario (e.g. Dewi et al. 2005).

It seems likely that the formation history of the DNS, and in particular the properties of the helium star, are imprinted onto the currently observed system parameters. For instance, a correlation between the spin-period of the pulsar and the system’s eccentricity is observed (McLaughlin et al. 2005; Faulkner et al. 2005). Based upon seven DNSs known at the time, it was argued that this relationship can be understood on evolutionary grounds (Faulkner et al. 2005) and the occurrence of low-velocity kicks during the second SN explosion (Dewi et al. 2005; van den Heuvel 2007). In the latter scenario, the SN is essentially symmetric and the post-SN properties are largely determined by the amount of mass lost during the explosion, such that greater mass loss leads to wider orbits and larger eccentricities. This low-kick scenario is particularly interesting, as together with the proposed formation of neutron stars in DNSs via an electron-capture SN (Podsiadlowski et al. 2005), it may explain simultaneously the spin-period eccentricity relationship and the low masses of the second born neutron star in some recent DNS discoveries (van den Heuvel 2007). In contrast, in an asymmetric SN, a kick and a corresponding large velocity are imparted to the neutron star and also determines the post-SN orbital configuration. Evidence for large kicks is observed in isolated pulsars (Hobbs et al. 2005) and can be inferred from the observations of geodetic precession in the binary pulsars PSR B1913+16 (Kramer 1998) and PSR B1534+12 (Stairs et al. 2004) (see also review by Kalogera et al. 2008). Clearly, the discovery of more Galactic disk DNSs will be extremely valuable to test and check the viability of the correlation and the proposed models.

In this Paper we describe the discovery and subsequent timing observations of PSR J1753–2240 which appears as a mildly-recycled 95-ms radio pulsar in an eccentric 14-d orbit. We argue that the system parameters suggest that the observable pulsar is the old component of a DNS, which allows us to investigate the implication for the spin-period/eccentricity relationship mentioned above.

2 DISCOVERY & FOLLOW-UP TIMING

PSR J1753–2240 was discovered during the re-assessment of candidates from the highly-successful Parkes Multibeam Pulsar Survey (e.g. Manchester et al. 2001). These candidates were produced during the processing of these data, as described by Faulkner et al. (2004) and were re-evaluated using improved data-mining tools developed and described

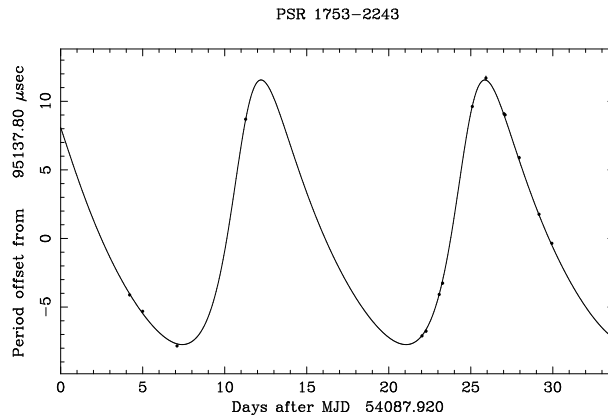


Figure 1. The apparent spin-period variation of PSR J1753–2240, showing the Doppler effect due to binary motion. The points show the barycentric period observed and the solid line shows the binary model with a 13.6-day orbital period and an eccentricity of 0.3 (Table 1).

by Keith et al. (2008). Following the identification and selection of appropriate candidates, observations were carried out at the Parkes telescope to confirm the pulsar origin of the detected signals. The receiver system was centred on 1374 MHz and used the original 96-channel survey filterbank and instrumentation (see Manchester et al. 2001 for details). Among the 30 newly-discovered pulsars, the source designated PSR J1753–2240 showed significant variations in its 95-ms period between various observations, indicating the presence of Doppler effects arising from an orbit around a binary companion to the pulsar. The apparent spin-period variations can be fully described by a 13.6-day eccentric Keplerian orbit, as shown in Figure 1. In order to precisely measure the positional, spin and orbital parameters, the pulsar was observed approximately twice a month for a period of 655 days using the Parkes telescope, producing 62 good time-of-arrival (TOA) measurements. The standard pulsar timing procedure (e.g. Lorimer & Kramer 2005) was then applied to fit these TOAs for the parameters using the TEMPO2 software, the results of which are detailed in Table 1. The integrated pulse profile obtained from summing several of these observations is shown in Figure 2.

3 RESULTS & DISCUSSION

The pulsar spin period of 95 ms is typical of that of a young pulsar, although the period derivative is measured to be $\dot{P} = (9.7 \pm 0.12) \times 10^{-19}$, implying a characteristic age of greater than 1 Gyr and a surface magnetic field strength of 9.7×10^9 G. These parameters strongly suggest that the pulsar’s evolution included a period of recycling where the binary companion has provided an episode of accretion induced spin-up. However, the relatively long spin-period implies that the accretion must have been relatively short-lived or otherwise ineffective.

3.1 Nature of the companion

Unlike superficially similar systems in globular clusters such as PSR J1748–2246J (Ransom et al. 2005), the chance

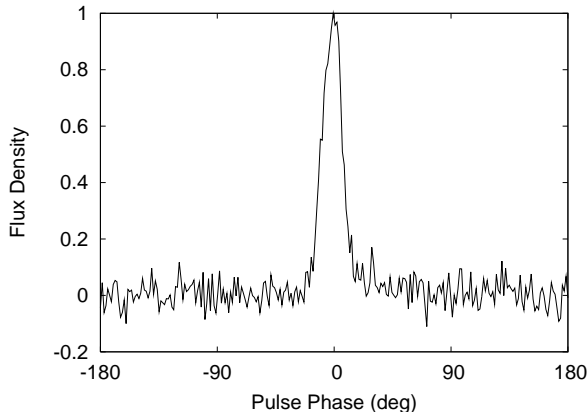


Figure 2. The integrated pulse profile of PSR J1753–2240 at 1374 MHz produced by summing data from 25 separate observations taken at Parkes. There are 256 phase bins across the profile. The y-axis is measured in arbitrary units of flux density.

Table 1. Observed and derived parameters of PSR J1753–2240, after fitting to 62 TOAs measured from MJD 54028 to 54683. The timing residuals relative to this model had an RMS of 0.4 ms. Errors in the last digit are shown in parentheses

RA (J2000 hh:mm:ss)	17:53:39.847(5)
Dec (J2000 dd:mm:ss)	−22:40:42(1)
Period (s)	0.0951378086771(7)
Period derivative (ss^{-1})	$0.00097(12) \times 10^{-15}$
Epoch (MJD)	54275.02
Solar System Ephemeris	DE405
Dispersion Measure, DM (pc cm^{-3})	158.6(4)
Flux Density at 1374 MHz (mJy)	0.15(3)
Pulse width at 10% of peak (ms)	8.6(6)
Binary Parameters	BT model
Orbital period (d)	13.6375668(7)
Epoch of periastron passage (MJD)	54099.13029(8)
Projected semi-major axis (lt-s)	18.11537(10)
Longitude of periastron (deg)	−49.3151(20)
Eccentricity	0.303582(10)
Characteristic Age (yr)	1.6×10^9
Characteristic Magnetic Field (G)	9.7×10^9
Mass function (M_{\odot})	0.0343
Minimum Companion Mass (M_{\odot})	0.4875
Distance* (kpc)	3

* derived from the NE2001 model of Cordes & Lazio (2002).

of creating binaries through exchange interactions in the Galactic disk is believed to be negligible. While recently an unusual and puzzling combination of orbital parameters has been found in the case of PSR J1903+0327 (Champion et al. 2008), the parameters observed here are commonly associated with mildly recycled pulsars where the companion object was responsible for the partial spin-up of the pulsar. Given the short spin-period and high orbital eccentricity, we consider it therefore as most likely that PSR J1753–2240 is a member of a DNS, with the detected pulsar being the first-born pulsar. In fact inspection of Table 2 clearly confirms that all the parameters of PSR J1753–2240 are in the typical range of DNS systems. The only exception is the minimum companion mass, which is smaller than for the other known DNSs. However we note that the observed mass function of the system allows for a companion significantly more massive than the minimum value shown.

Orbital parameters can provide some restrictions on the companion mass, based upon geometry. Assuming a random distribution of orbital orientation and a nominal pulsar mass of $1.4M_{\odot}$ we derive from the mass function at a 95% confidence level that the companion mass is less than $2.5M_{\odot}$ (for $i \approx 18^{\circ}$). This implies a maximum system mass of around $4M_{\odot}$ and a semi-major axis of approximately 36 light seconds. If we allow a reasonable range of pulsar and companion masses such that they lie between 1.2 and $1.8M_{\odot}$, the measured mass function implies an inclination angle range of $22^{\circ} \leq i \leq 34^{\circ}$, which has a nominal probability of 10% of occurring in a randomly selected system.

If the companion is a second neutron star, it is possible that it also may be detectable as a radio pulsar. Long, 2.5-hour observations of PSR J1753–2240 using the same Parkes observing system at 1374 MHz were carried out in a search for the companion, but no pulses have been detected. The sensitivity of the search implies that the companion, has an apparent 1400-MHz luminosity of less than 0.9 mJy kpc². Only $\sim 6\%$ of all known pulsars with published 1400-MHz flux density measurements have luminosities below this limit.

Searches for a white-dwarf or a main-sequence companion in archival optical and infra-red data sets have not been successful, although deeper observations would be required to rule out either type of companion. Given the DM estimated distance of ~ 3 kpc and the small Galactic latitude of $b = 1.5$ deg, a white dwarf would have a V-band magnitude of ~ 26 , which is within the reach of large optical telescopes.

3.2 Spin-period – eccentricity relationship

If J1753–2240 is indeed a partially recycled pulsar in a DNS system, we can consider how it relates to other DNSs. We are particularly interested in how it fits into the relationship found between the orbital eccentricity and the spin-period of the first-born pulsar (see Section 1). For this reason, we exclude the two known DNSs J1906+0746 and B2127+11C. The latter is in a globular cluster and was probably formed via an exchange interaction rather than by binary evolution (Prince et al. 1991). In contrast, PSR J1906+0746 is likely to be a second-born young pulsar (Lorimer et al. 2006) and the period of the first-born neutron star is unknown. A com-

parison of the parameters for the remaining seven DNS systems and J1753–2240 is given in Table 2.

In Figure 3 we show the updated plot of eccentricity versus orbital period as presented by Faulkner et al. (2005) but now including PSR J1753–2240. Our suggested DNS, PSR J1753–2240, has a much smaller eccentricity or longer period than suggested by the correlation seen in the other seven DNSs. Given the assumed hypothesis regarding the nature of the system there are three possible explanations for this: (a) the system was formed in an unlikely or unusual formation process with a relatively small mass loss, or a rather fortuitous kick during an asymmetric supernova explosion, (b) the previously inferred relationship between spin-period and eccentricity arose from the low-number statistics, or (c) the pulsar has spun down during its lifetime to move away from the spin-eccentricity line. We consider these possibilities in turn.

It is possible that the formation mechanism of the J1753–2240 system is somehow different from that of the other selected DNSs. However, looking at Table 2, there is little evidence to suggest that the J1753–2240 system is significantly different in nature from the other DNSs, we will assume for the rest of this discussion that the formation mechanism of this system is not unique amongst the known DNSs.

It is obviously very difficult to make a clear statement about the reality of the spin period – eccentricity relationship as the number of involved DNS systems is still small. However, the possible physical origin of such a relationship was also studied by Willems et al. (2008) who investigated whether the observed relation can be produced by assuming that kicks are restricted to be along the rotation axis of the NS progenitor. Such an assumption is motivated by the observation of an alignment of the velocities vectors of pulsars with their rotation axis (Johnston et al. 2005). It is not clear however that the kick must be aligned with the pre-SN rotation axis as a post-SN alignment can also be produced for kicks directed away from the pre-SN rotation axis, depending on the relative duration of the kick mechanism and the initial spin period of the pulsar (Spruit & Phinney 1998).

Assuming “polar kicks”, i.e. kicks to the second-born neutron stars constrained to be within 10° of the progenitor’s rotation axis, no correlation appears for large kick velocities typical of isolated pulsars (Willems et al. 2008). When low kicks are imparted, the correlation can be well produced, supporting the case for a low-kick scenario, at least in the case of the standard formation scenario. However, when constrained to a low kick velocity, the standard formation models are unable to reproduce the spin-orbit mis-alignment angles observed in PSR B1913+16 (Willems et al. 2004). Hence, Willems et al. suggest that systems like PSR B1913+16 may be formed via a second, different formation channel, where no mass transfer occurs after the common envelope phase and large kicks with magnitudes inferred for isolated pulsars are imparted on the second-born neutron star. PSR J1753–2240 may represent such a system where the kick was large enough to produce a significant eccentricity while the total amount of recycling was small.

On the other hand, in the work of Dewi et al. (2005, 2007) no second formation channel is invoked, but their simulations can also reproduce the observed correlation by

simply assuming that the births of the second born neutron stars in DNSs are accompanied by moderate supernova kicks (less than 50 km s^{-1}) and that the physical parameters of the DNSs are determined by the evolution of Helium-star – neutron-star binaries. The orbital eccentricity is produced primarily by the sudden mass loss in the second supernova explosion. Despite the success in explaining the observed trend, there is a large spread in the final properties of the simulated population, and the authors are forced to disregard the kinematically derived large kicks for PSRs B1913+16 and B1534+12 (Willems et al. 2004). Inspecting Dewi et al.’s result, we notice that the seven previously known DNSs are essentially lying along the upper envelope of systems in the Dewi et al. simulations (see Figure 3). At the same time, our newly discovered pulsar appears much closer to the majority of the simulated pulsars than the known pulsars. From this point of view, it is suggestive to assume that the observed system parameters are in fact typical and that the deviation of the new point from the correlation simply reflects the statistical variation and the different conditions that lead to the spread in system parameters seen by Dewi et al.

The simulations by Dewi et al. take the evolution of the orbital parameters due to the emission of gravitational waves into account, but it is unclear to us as to whether they also include the spin evolution of pulsars. Due the small spin-down rates, the evolutionary timescales are long, but one can speculate as to whether including the spin evolution would tend to smear out any relationship existing at birth of the systems. Using the standard spin-period evolution model (e.g. Lyne & Smith 2005), we can estimate the time it may have taken the pulsar to move away from the suggested line of the spin period-eccentricity relationship. For a braking index of $n = 3$, it would have taken $1.1 \times 10^9 \text{ yr}$ for the pulsar to move from $P_0 = 40 \text{ ms}$ to the observed period of $P = 95 \text{ ms}$. As the simulations by Dewi et al. in fact suggest a broad band for the actual relationship, the actual evolution time could be even smaller, but it raises the question why the previous known systems would then still follow a common relationship. We suggest that future studies consider this possible complication in some detail.

3.3 Future observations

It has been argued (Podsiadlowski et al. 2005; van den Heuvel 2007) that low-kick births of neutron stars in DNS systems may be the result of a new formation channel for neutron stars. In such a case, the neutron star may not be formed in the collapse of the massive iron core, but instead in an “electron-capture” supernova, in which a slightly less massive O-Ne-Mg core starts capturing electrons onto Mg to initiate the collapse (Nomoto 1984, Podsiadlowski et al. 2004). If such a process were indeed also responsible for forming the observed system of PSR J1753–2240, then very definite predictions could be made about the mass of the pulsar’s companion, since possible progenitor baryonic masses are expected in a small range near $1.37 M_\odot$. The mass of the finally formed companion neutron star would then have this progenitor mass less the gravitational binding energy of the neutron star, suggesting companion masses of around $1.25 M_\odot$ (depending on the neutron star’s equation of state, Podsiadlowski et al. 2005).

Table 2. Summary of the parameters of the seven known first-born pulsars in Galactic DNS systems and PSR J1753–2240. Pulsars are ordered by their spin-period. Except where shown in parentheses, errors in values are smaller than the number of significant figures shown.

	J0737–3039A	J1756–2251	B1534+12	J1518+4904	J1829+2456	B1913+16	J1753–2240	J1811–1736
P_{spin} (ms)	22.69	28.46	37.90	40.93	41.01	59.03	95.13	104.18
$\dot{P}_{\text{spin}} (\times 10^{-18})$	0.2	0.1	2	0.03	0.05	8	1	0.9
P_{binary} (day)	0.10	0.32	0.42	8.63	1.17	0.32	13.63	18.77
$A_p \sin(i)$ (lt-s)	1.41	2.75	3.73	20.04	7.23	2.34	18.11	34.78
e	0.08	0.18	0.27	0.24	0.14	0.62	0.30	0.83
τ_c (MYr)	204	443	249	23000	12400	108	1500	1830
$B_{\text{surf}} (10^{10} \text{ G})$	6.4	5.4	9.7	1.0	1.5	2.3	0.97	9.8
$\text{Min}[m_c] (M_{\odot})$	1.25	1.10	1.30	0.81	1.26	0.87	0.49	0.93
m_c	1.2489(7)	1.26(2)	1.3452(10)	-	-	1.3867(2)	-	-
Reference	(1)	(2)	(3)	(4)	(5)	(6)	-	(7)

References: (1)Kramer et al. (2006), (2)Ferdman (2008), (3)Stairs et al. (2002), (4)Janssen et al. (2008), (5)Champion et al. (2005), (6)Weisberg & Taylor (2005), (7)Corongiu et al. (2007).

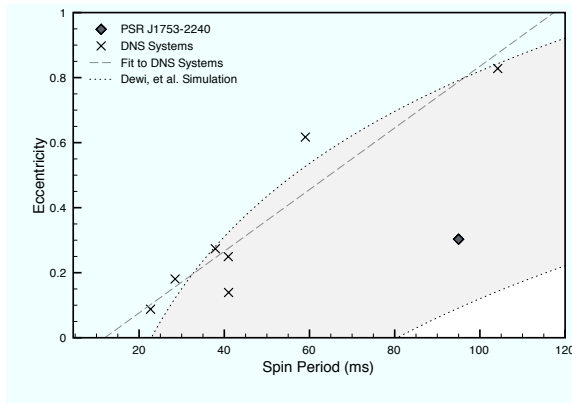


Figure 3. The spin-period and eccentricity for the seven double neutron star systems and PSR J1753–2240. The long dashed line shows a linear fit to the seven double neutron star systems. The grey shaded area shows the approximate region for which the simulations in Dewi et al. (2005) produced most systems. This area does not reflect the density of simulated points in any way.

Further timing of PSR J1753–2240 will eventually be able to test this hypothesis as it will lead to better constraints on the total system mass, using a future detection of a relativistic periastron advance. Simulations using the TEMPO2 ‘fake’ plugin (Hobbs et al. 2006) suggest that given a pulsar and companion mass of $\sim 1.25M_{\odot}$ the advance of periastron will be detectable at the $5\text{-}\sigma$ level within 4 years. At the same time, we will conduct deep optical observations in order to attempt detection of the optical emission of any white dwarf or main-sequence star companion.

4 CONCLUSIONS & SUMMARY

PSR J1753–2240 shows many of the features of a DNS binary, however it also shows some dissimilarities. In the first instance, the mass function of the system is somewhat lower than those of the other similar DNS systems, however the required orbital inclination is not unreasonable. The system also lies far from the relationship between spin period

and eccentricity suggested for DNS systems. Nevertheless we argue that the most likely companion is another neutron star, principally because of the partially recycled nature of the system and the observed orbital parameters. Regardless of the companion type, PSR J1753–2240 is an interesting system, lying in a poorly sampled region of the spin period/orbital period/eccentricity phase space. Therefore it will be important to continue observations, to further constrain the system mass and also to monitor the long-term evolution of the system. If the DNS nature of the system is indeed confirmed (or rejected) by future radio, optical or infra-red observations, the system provides an interesting case for the question about high- or low-kick formation of neutrons stars, illuminating the question about the validity, range and/or origin of the spin-eccentricity relationship.

ACKNOWLEDGEMENTS

This research was partly funded by grants from the Science & Technology Facilities Council, UK. The Australia Telescope is funded by the Commonwealth of Australia for operation as a National Facility managed by the CSIRO. The authors would like to thank the following people for their contributions to observing at Parkes: M. Burgay, A. Notsos, G. Hobbs, J. O’Brien, A. Corongiu, M. Purver, R. Smits and C. Espinoza.

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